Assessing the Impact of Laser- Plasma Instabilities, Hot Electron Fluxes and Far from Equilibrium Kinetic States in Burning Plasmas

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Lawrence Livermore National Laboratory

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$\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$ $\frac{e^2}{\hbar c} \approx \frac{1}{137}$

* **Work supported by DOE Joint Program in HEDLP and by LLNL**

Big Picture: Follow (Or Lead) the Hot e^-s & Do Constrained Optimization, via Learned Compression in Fully Kinetic Simulations of e^-s and ions and EM fields

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- Try to exploit laser-plasma instabilities to probe non-thermal, non-steady state, non-equilibrium and non-fluid-model-capturable effects in high energy density plasmas.
- Nonlinear optical processes render a plasma kinetic and non-fluid like over fast time scale (sub-ps) and short length scale (10-100 μm) evolving distribution functions for electrons and (~ 10 times slower for) ions.
- Need new experiments, new diagnostics, new simulations and new theoretical models coupling imploding shell dynamics to shocked interface physics, ice-gas interface, ablator-ice interface and wall-fill gas interfaces.
- You don't get rid of LPI (as if you could!). You learn about your plasma using LPI. You also control LPI by properly designing laser pulses on the LPI relevant space and time scales (The STUD pulse program).
- New codes must use parsimonious representations of phase space, be adaptive and learn from previous simulations by compressing information to capture essential length, velocity and time scales and constraining nonlinear solvers in fully implicit approaches by such accumulated data. Bootstrap to ever more rapid convergence via variational constraints.

Hohlraums Contain Plasmas at Different Conditions (n_e, T_e, u, f_e(v)) in Different locations at Different Times, Made of He, Be, CH, C, Ne, SiO_2, U, Au, …

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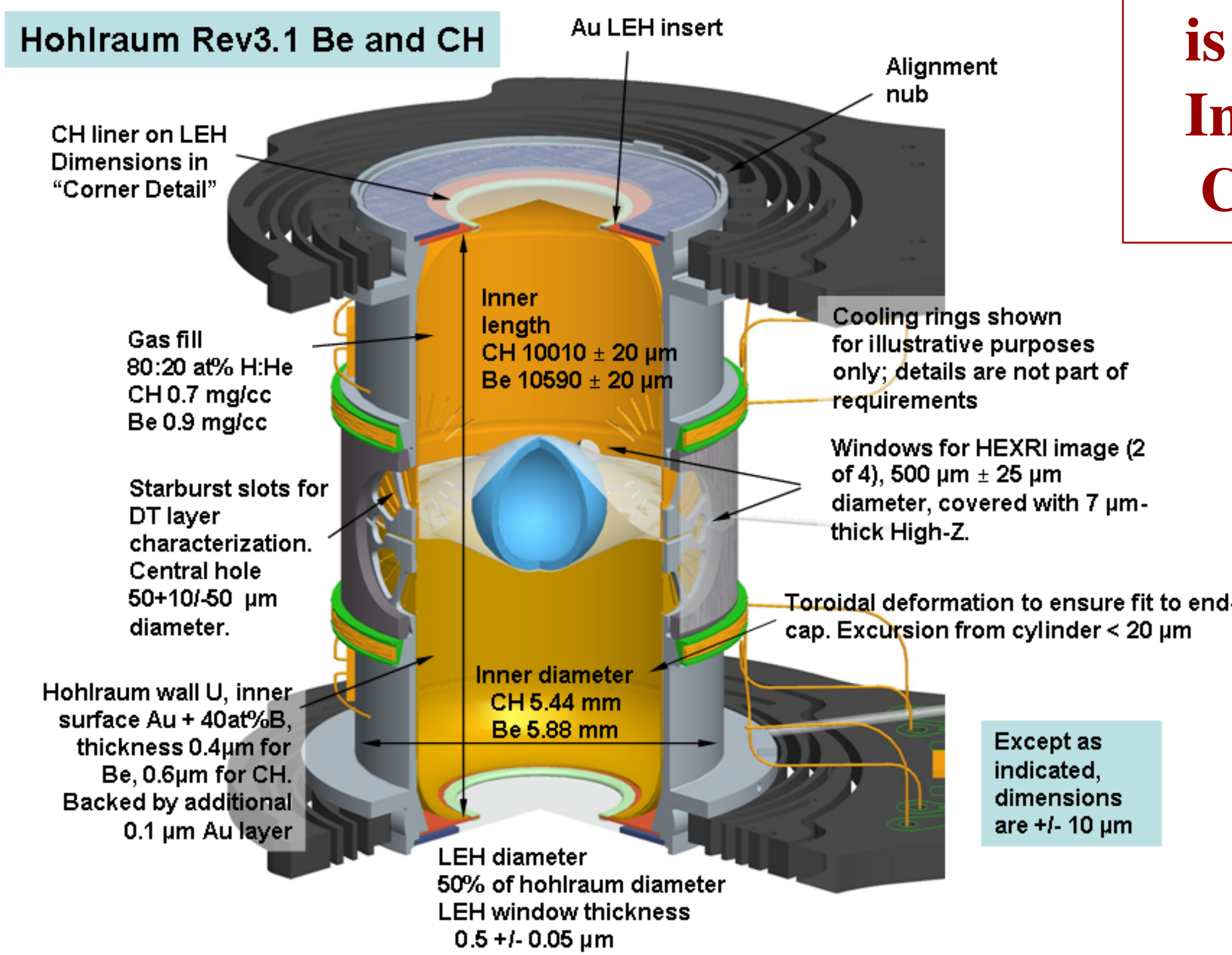
NIF has P_{drive} > 100 MB, and has achieved P_{Stag} > 150 – 200 GB but needs P_{Stag} > 300 GB to ignite at < 2 MJ.



A NIF Hohlraum is a Laser-Plasma Instability (LPI) Candy Store

Non of the plasma conditions or interaction modalities that are manifest on the NIF were ever accessed on Nova or Omega.

It's all different and yet It remains weakly characterized, weakly diagnosed, and studied only in passing.

Adequate Stringent Control of Laser-Plasma Instabilities Is Required to Achieve Indirect or Direct Drive Ignition

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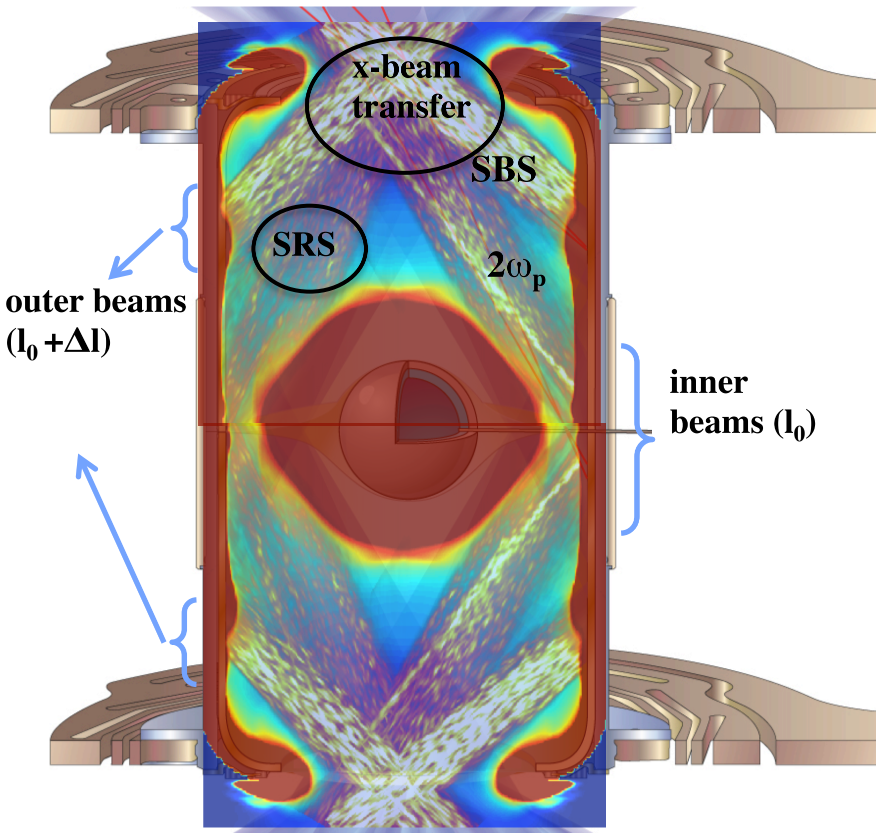

- **Energy coupling should be > 90% to achieve high enough T_{rad}**

- **Implosion symmetry requires controlled power balance between "inner" and "outer" beams. Soft X-ray flux on equator vs. poles in space *and* time must be maintained.**

- **Must have low capsule preheat (T_{hot}, f_{hot})**

- **Must control SBS, SRS, $2\omega_p$ & filamentation, cross-beam energy transfer (CBET), hot electron and hard X ray (M Band) proliferation.**

The Geometry of NIF Quads: Top View, 4 Cones: Inner (Red 23º, Orange 30º) & Outer (Dark 44º & Light Green 50º)

48 Quads in Total:
16 Outer and 8 Inner
Per Hemisphere

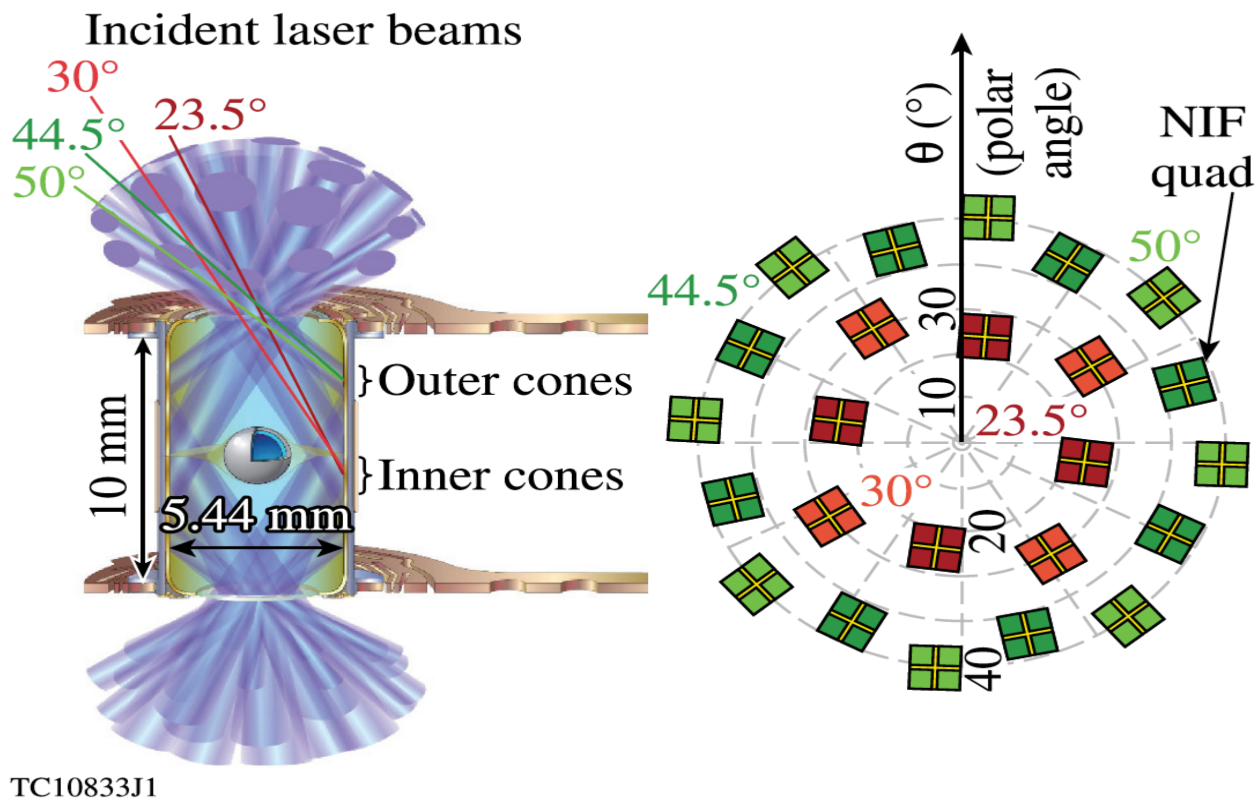

FIG. 1. Left: A schematic of a NIF ignition *Hohlraum* with the approximate dimensions, showing the inner and outer beam cones entering the *Hohlraum* through the two laser entrance holes. Right: The specific angles of the NIF beam quads, which are color coded: inner quads orange ($\theta = 30°$) and red ($\theta = 23.5°$), outer quads light ($\theta = 50°$) and dark green ($\theta = 44.5°$), where θ is the polar angle.

Dispersion Relations of Waves Whose Three Wave Couplings Give Rise to Laser Plasma instabilities

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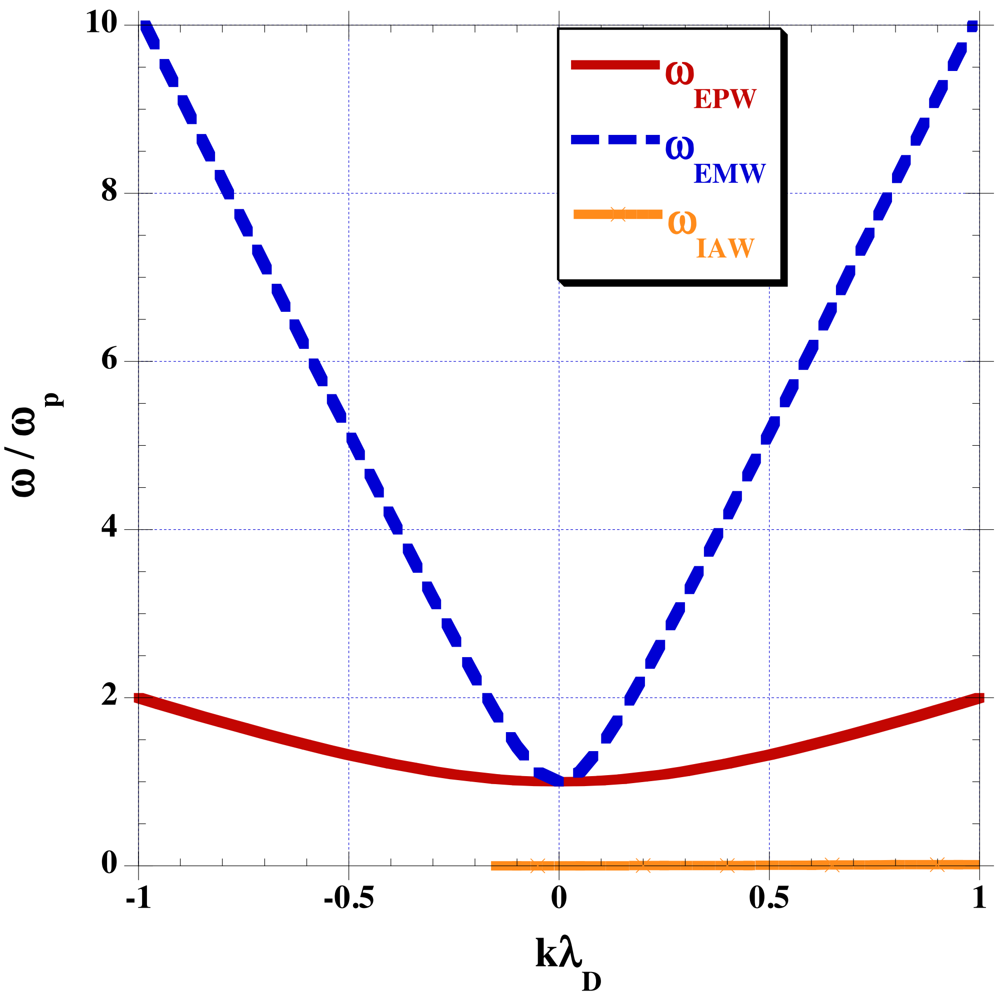
Dispersion Relations of EPWs, EMWs and IAWs in Uniform Plasmas



$$\omega_{\mathrm{EMW}}^2 = \omega_p^2 + c^2 k_{\mathrm{EMW}}^2$$

$$\omega_{\mathrm{EPW}}^2 = \omega_p^2 + 3\,\mathrm{v}_{th}^2\, k_{\mathrm{EPW}}^2$$

$$\omega_{\mathrm{IAW}} = \mathbf{u} \bullet \mathbf{k}_{\mathrm{IAW}} + c_s k_{\mathrm{IAW}}$$

$$\boxed{\begin{aligned} \omega_0 &= \omega_1 + \omega_2 \\ \mathbf{k}_0 &= \mathbf{k}_1 + \mathbf{k}_2 \end{aligned}}$$

$$\omega_{\mathrm{EMW}} = \sqrt{1 + \left(511 / T_{e,keV}\right) k_{\mathrm{EMW}}^2}$$

$$\omega_{\mathrm{EPW}} = \sqrt{1 + 3\, k_{\mathrm{EPW}}^2}$$

$$\omega_{\mathrm{IAW}} = \sqrt{\frac{Z\, m_e}{M_I}}\; k_{\mathrm{IAW}}$$

Most Prominent LPI Processes Are: SRS, SBS, $2\omega_p$ & Filamentation

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SRS EMW --> EMW + EPW

Very dangerous Instability for indirect drive ICF. Did in the Shiva Laser at 1 μm back in the 70's. Almost equal amounts of hot e- generation and Backscattering

$$\omega_0 = \omega_1 + \omega_2$$
$$\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2$$

SBS EMW --> EMW + IAW

Very dangerous Instability for indirect drive. Almost all the energy goes to the scattered light wave. Velocity gradients can potentially tame it.

2Wp EMW --> EPW + EPW

Very dangerous instability for direct drive. It has the lowest intensity threshold, all the energy goes to coherent high frequency oscillations of the plasma and then perhaps to IAWs but with preheat getting you first.

FIL Breakup of the laser light into dancing filaments. Really a 4 wave process including both Stokes and Anti-Stokes components interacting with a degenerate zero frequency IAW. Related to Self-Focusing in classical NLO.

We Can Make Rough Estimates for the Thresholds for Self-Organization in Continuously Driven LPI:

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$$I_{14}^{2\omega_p} \geq 1.62 \frac{T_{e,keV}}{L_{n,100\,\mu m}\,\lambda_{0,0.35\,\mu m}}$$

$\boxed{\text{EMW --> EPW + EPW}}$

$2\omega_p$ (Absolute modes)

$$I_{14}^{SBS} \geq 17 \frac{T_{e,keV}}{L_{v,100\,\mu m}\,\lambda_{0,0.35\,\mu m}} \left[\frac{0.1}{(n/n_c)}\right]$$

$\boxed{\text{EMW --> EMW + IAW}}$

SBS (Convective modes)

$$I_{14}^{SRS} \geq 120 \frac{T_{e,keV}}{L_{n,100\,\mu m}\,\lambda_{0,0.35\,\mu m}}$$

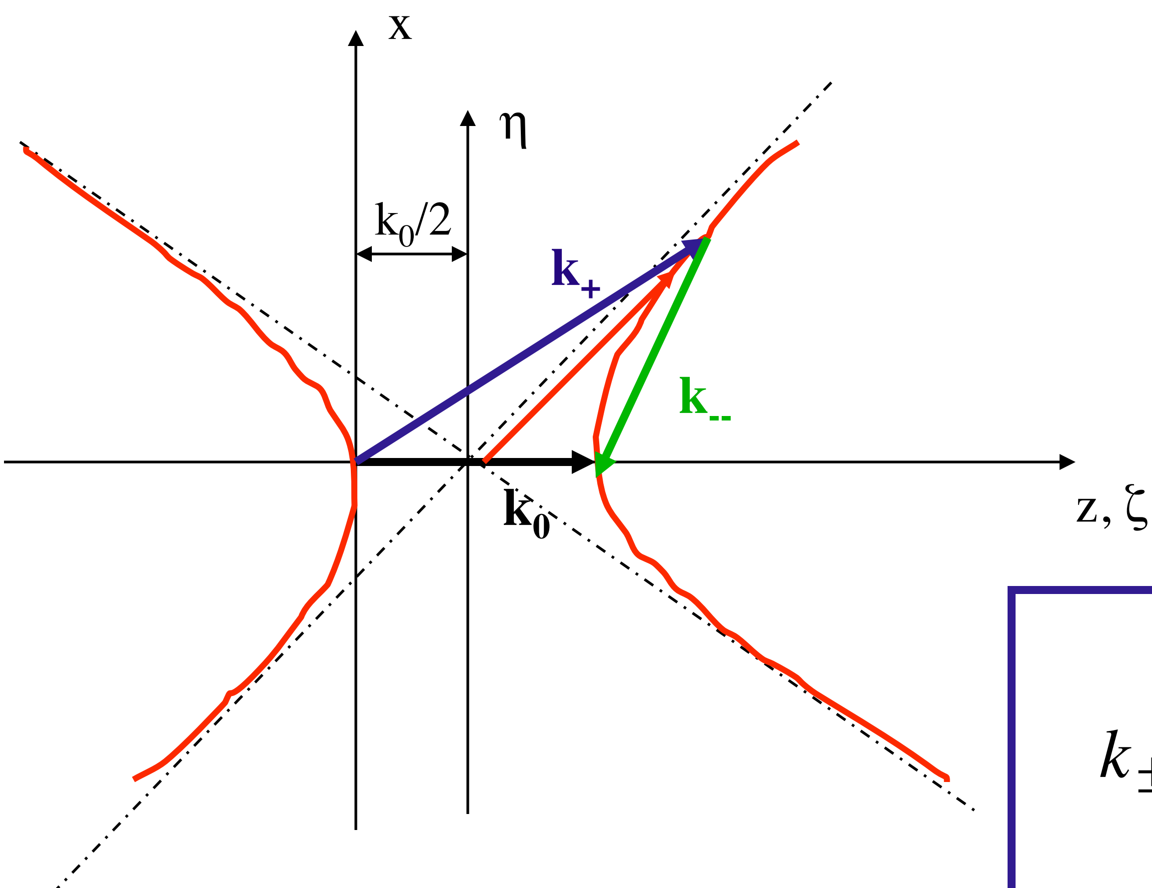
SRS (Convective modes)

$\boxed{\text{EMW --> EMW + EPW}}$

Typical hot spot gain lengths are $\sim 4 f^2 \lambda_0 = 90\ \mu m$ for $f/8$
$= 560\ \mu m$ for $f/20$

At intensities approaching 10^{15} W/cm^2, as in the peak of NIF pulses, you are well above threshold for all three. SRS mostly in hot spots or blame it on a multitude of beams making common cause.

Maximum Growth Rate Hyperbola Defines Most unstable $2\omega_{pe}$ Modes:



$$\varsigma^2 = \frac{\varepsilon}{4} + \eta^2$$

$$k_{\pm} = \sqrt{\left(\frac{\varepsilon}{4} + \eta^2\right)^2 \pm \frac{\sqrt{\varepsilon}}{2}}$$

Universal Normalized Growth Rate for $2\omega_p$

$$\bar{\Gamma}^{2\omega_p} = 1 - \bar{v}(\bar{\eta}) - \bar{\eta}^2/2 - D/|\bar{\eta}|$$

$$\bar{\eta} \equiv \tilde{\beta}\eta \qquad D = \frac{\varepsilon_L\ \tilde{\beta}}{2\ \tilde{v}_0}$$

For Seka's Omega parameters:D~0.113
ie $D_{thresh}/D \sim 4.8$, roughly 5x above threshold.
Expect lots of nonlinearity (and will find it!)

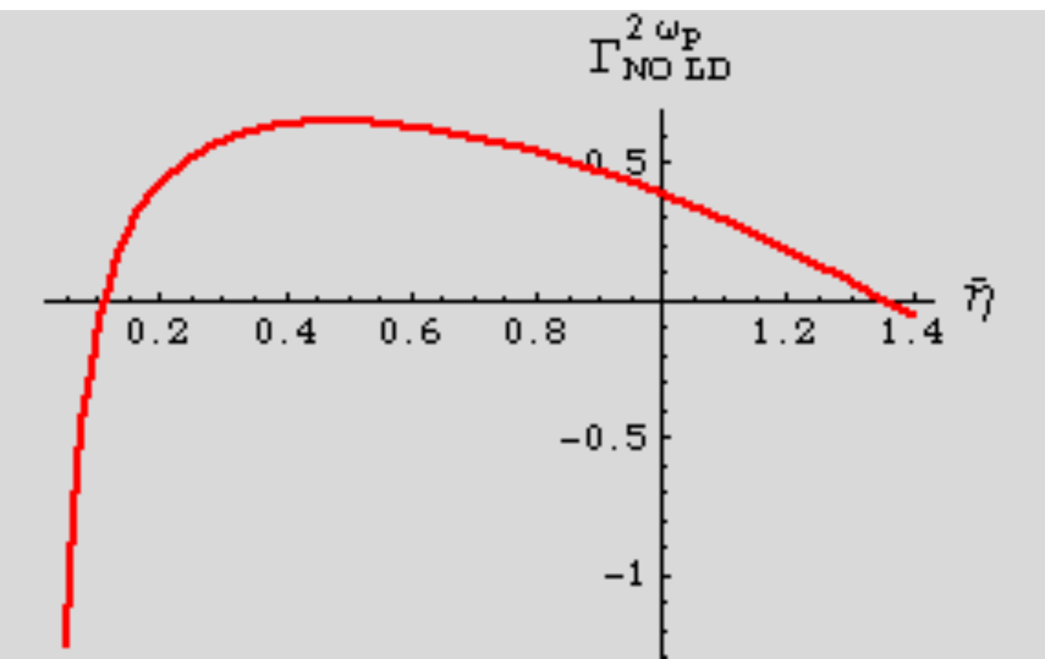
$$D = 0\ 3\ \frac{T_{keV}}{\left(I_{14,W/cm^2}\lambda^2_{o,\mu m}\right)\left(L_{100\mu m}/\lambda_{o,\mu m}\right)}$$

$$\bar{\eta}_{thresh} = \sqrt{\frac{2}{3}} \qquad D_{thresh} = \left(\frac{2}{3}\right)^{3/2}$$

$$\bar{\eta}_{peak} = D^{1/3}$$

$$\bar{\eta}_{\min} \approx D\left[1 + \frac{D}{2\left(1 - 3\ D^2/2\right)}\right]$$

$$\bar{\eta}_{\max} \approx \sqrt{2}\left[1 - \frac{D}{2^{3/2}} - \frac{3}{16}D^2\right]$$



Let' s Plug in Some Numbers:

For the most unstable mode (at the peak of the growth rate curve), at threshold, the perpendicular component of the the wavevector of the plasmons is given by:

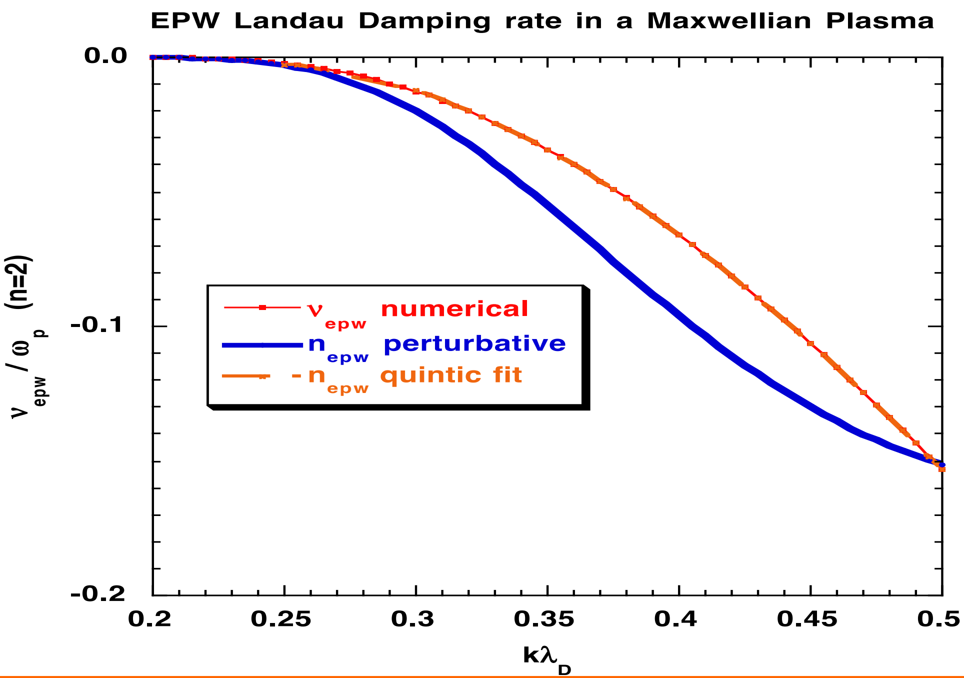
$$\frac{\lambda_{\perp,peak}}{\lambda_0} = \sqrt{\frac{3}{2}}\,\tilde{\beta} = 3.368 \times \frac{T_{e,keV}}{\sqrt{I_{14\,W/cm^2}}\,\lambda_{0,\mu m}}$$

We will affect the growth rate of this mode if the lateral extent of the hot spot is of this order. That condition becomes:

$$f/\# < 1.68\,\frac{T_{e,keV}}{\sqrt{I_{14\,W/cm^2}}\,\lambda_{0,\mu m}}$$

Landau Damping Rate of an EPW in a Maxwellian Plasma for $k\lambda_D > 0.25$ Is Well Approximated By:

$$\frac{\nu_{epw}}{\omega_p}\left(n=2, k\lambda_D > 0.25\right) \approx -0.23 + 2.2\left(k\lambda_D\right) - 6.6\left(k\lambda_D\right)^2 + 6.8\left(k\lambda_D\right)^3 - 3.9\left(k\lambda_D\right)^4 + 0.96\left(k\lambda_D\right)^5$$



$$\alpha_e = \left[\frac{3\,\Gamma(3/n)}{\Gamma(5/n)}\right]^{1/2}$$

$$\frac{\nu_{epw}}{\omega_p}\left(n, k\lambda_D < 0.25\right) \approx -\frac{\pi}{4}\left[\frac{n}{\Gamma(3/n)\,\alpha_e^3}\right]\frac{1}{\left(k\lambda_D\right)^3}\exp\left[-\frac{1}{\left(\alpha_e k\lambda_D\right)^2} - \left(\frac{3n}{2\,\alpha_e^n}\right)\frac{1}{\left(k\lambda_D\right)^{n-2}}\right]$$

For ICF, Landau Damping Could Play a Significant Role in Dictating Mode Selection for $2\omega_p$ with High T_e

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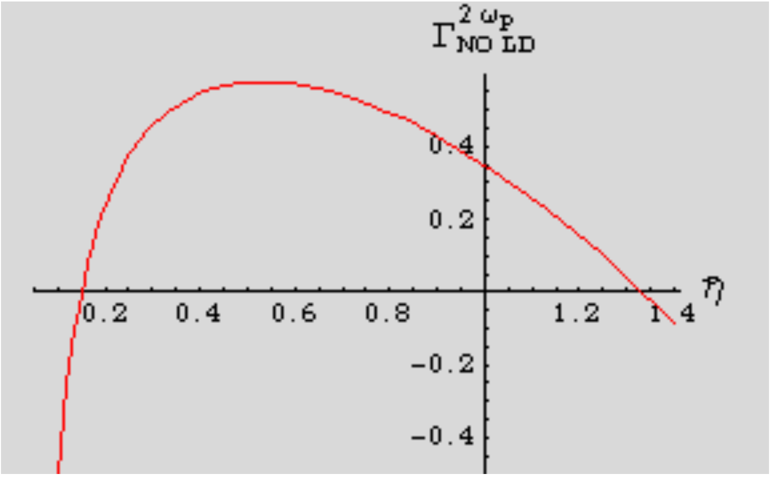

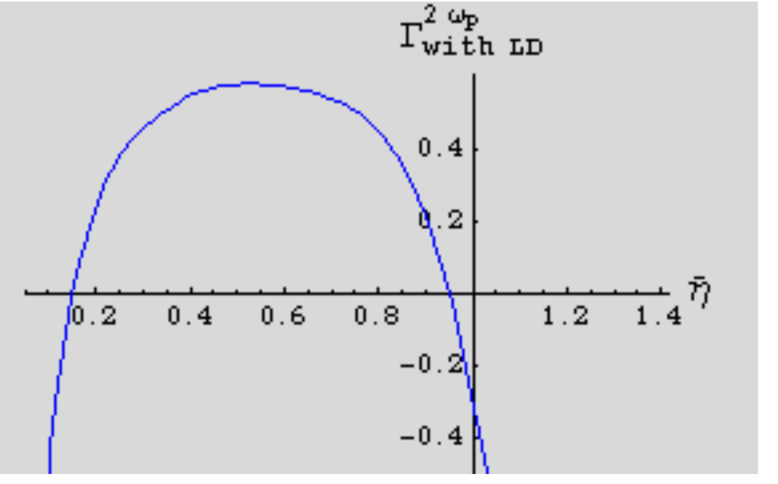

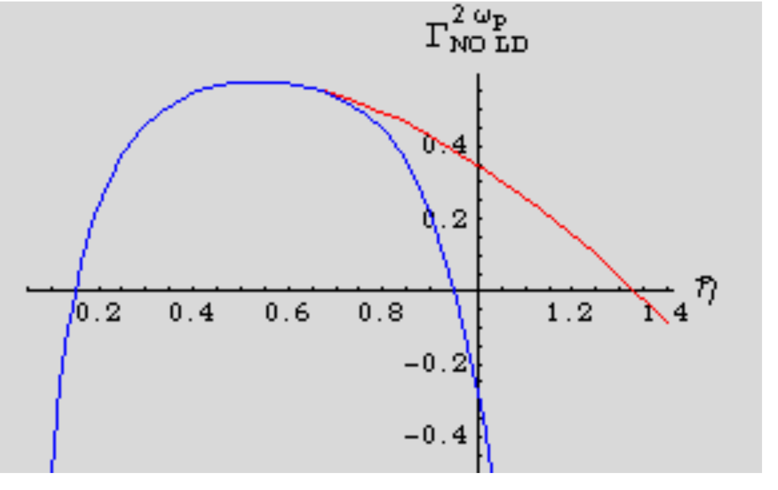

Picket hot electrons generation regions and deposition in high-Z capsule surrogate were inferred from hard x-ray Bremmstrahlung imaging of target emission*

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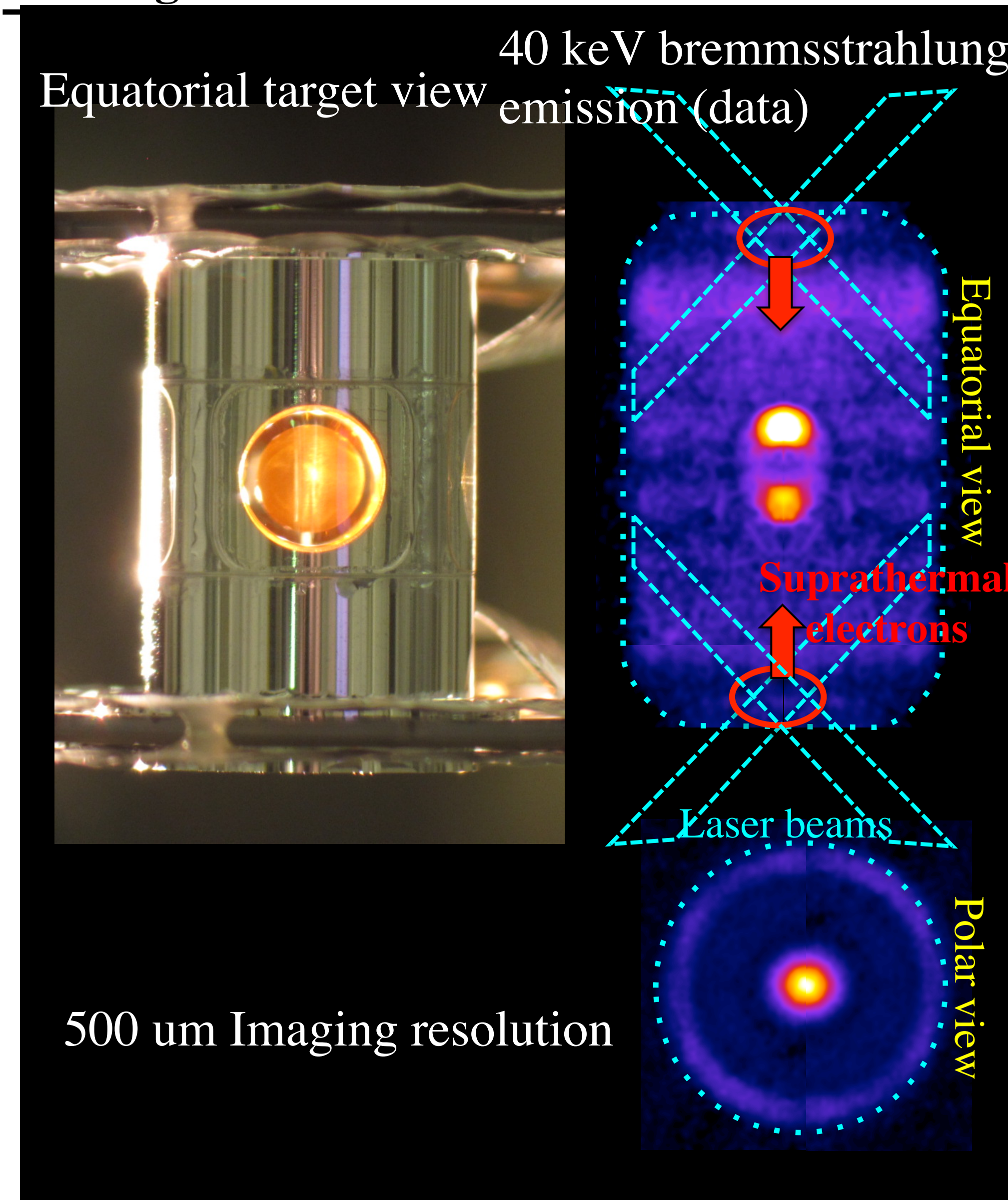
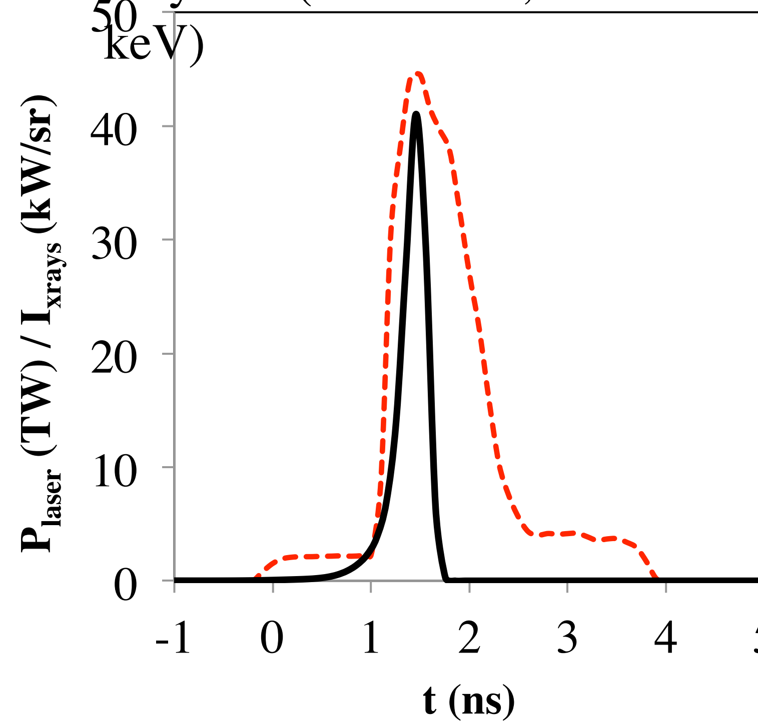


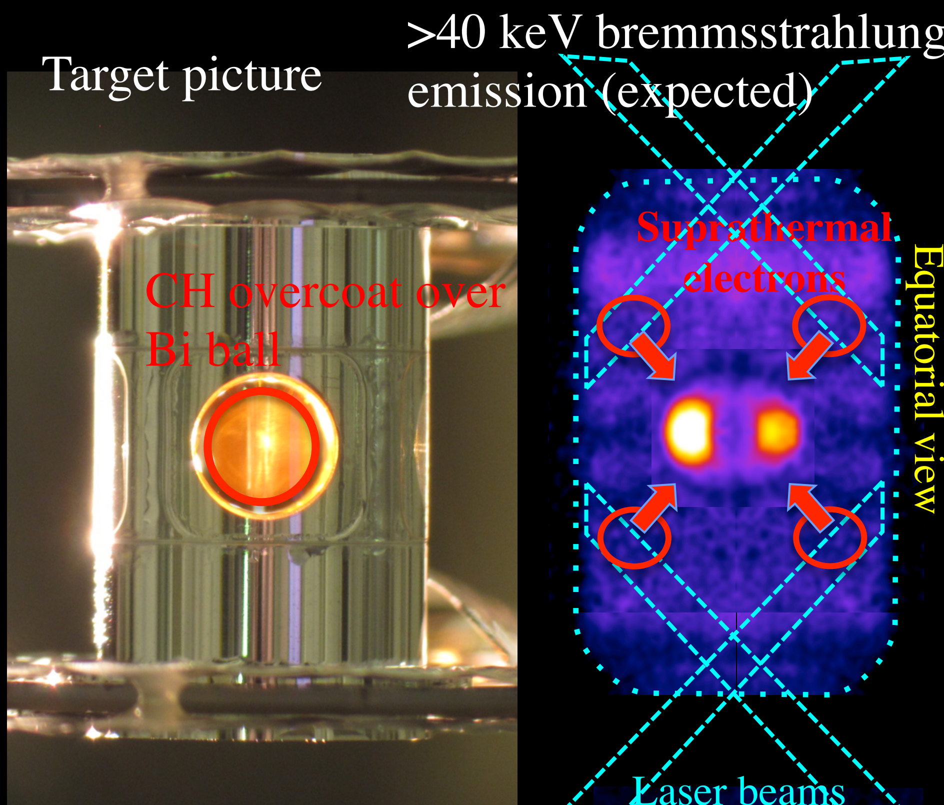
Typically picket hot electrons are emitted as a 200 ps burst and are very low (Ehot ~10J, Thot ~40 keV)

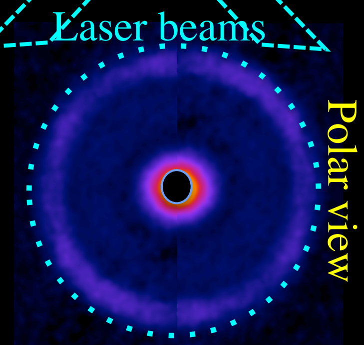


To separate picket hots, ICF laser pulse was truncated after the picket

* E. Dewald et al, Phys. Rev. Lett. 2016

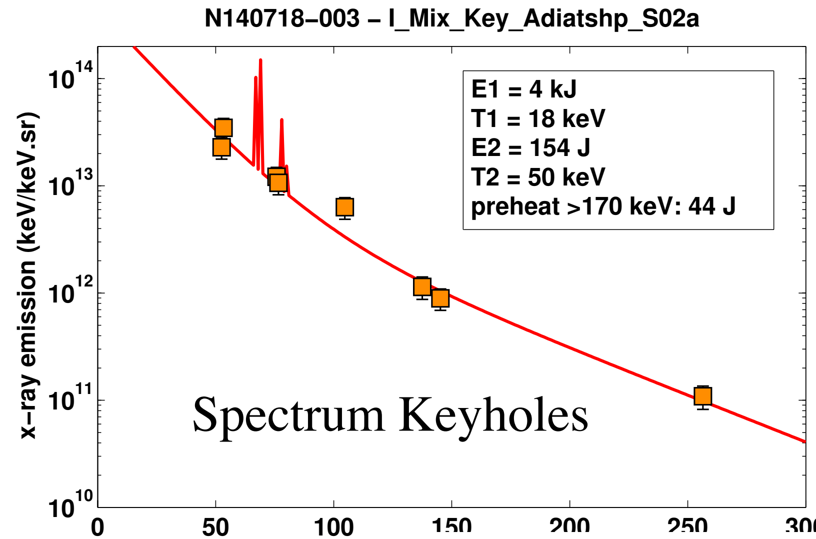
Same technique can be applied for the rise of the main pulse (creating large amount of SRS) by adding CH coating to the Capsule surrogate to maintain ICF hydro and LPI conditions



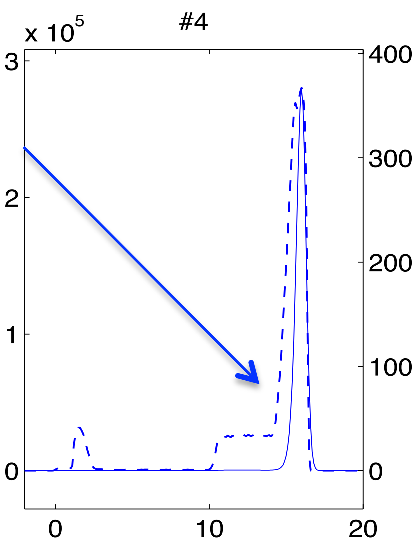


- Improved resolution will be achieved (~100 um) due to higher hot-e amount

20-40x more hots are expected than in the picket for HiFoot, high fill cond.

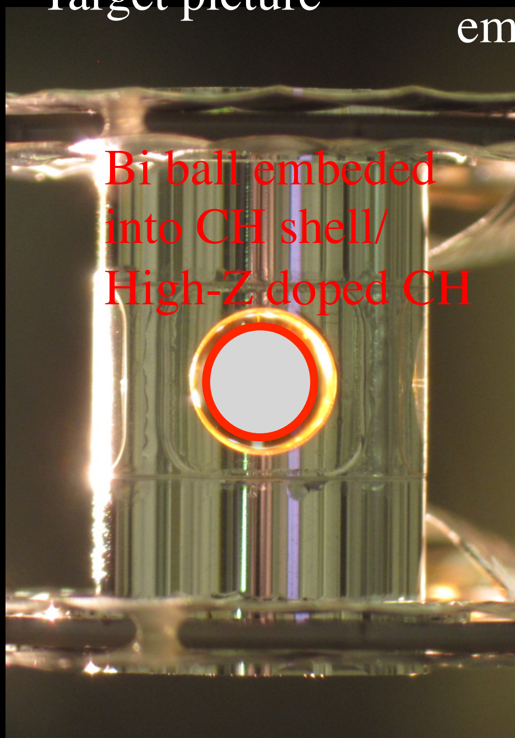


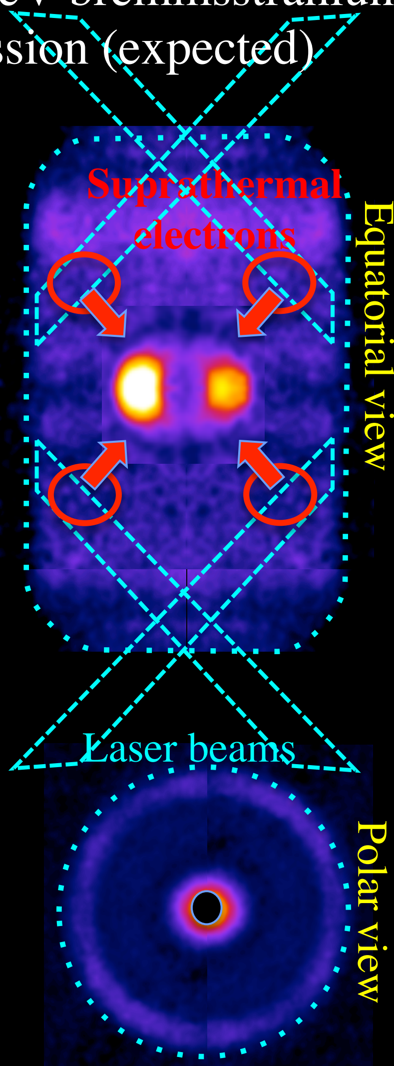
Hot-e x-rays (solid)
Laser power (dashed)



- Overcoat (<20% of initial mass) works since capsule does not implode much in the rise

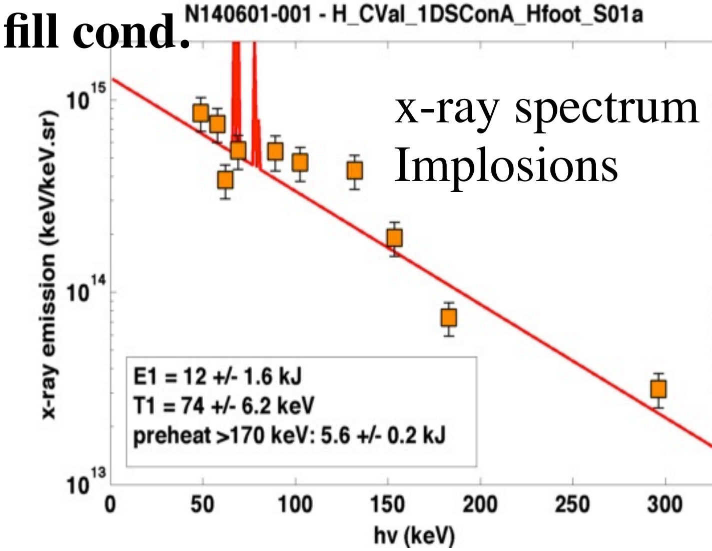
For the peak, capsule has to be replaced by high-Z sphere embedded into imploding ablator (or add High-Z dopant to ablator) to keep hydro equivalency



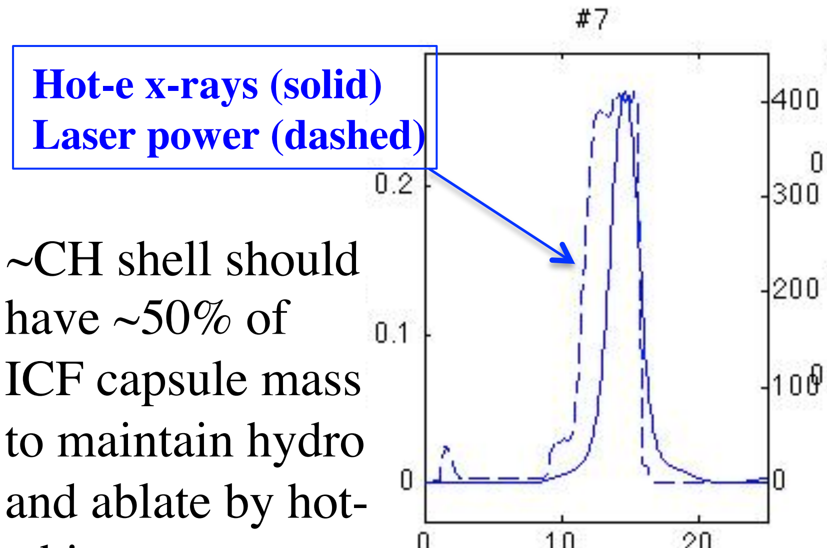


- 50 um resolution and gated imaging (Axis) is possible in the peak

>100x more hots are expected than in the rise for HiFoot, high fill cond.



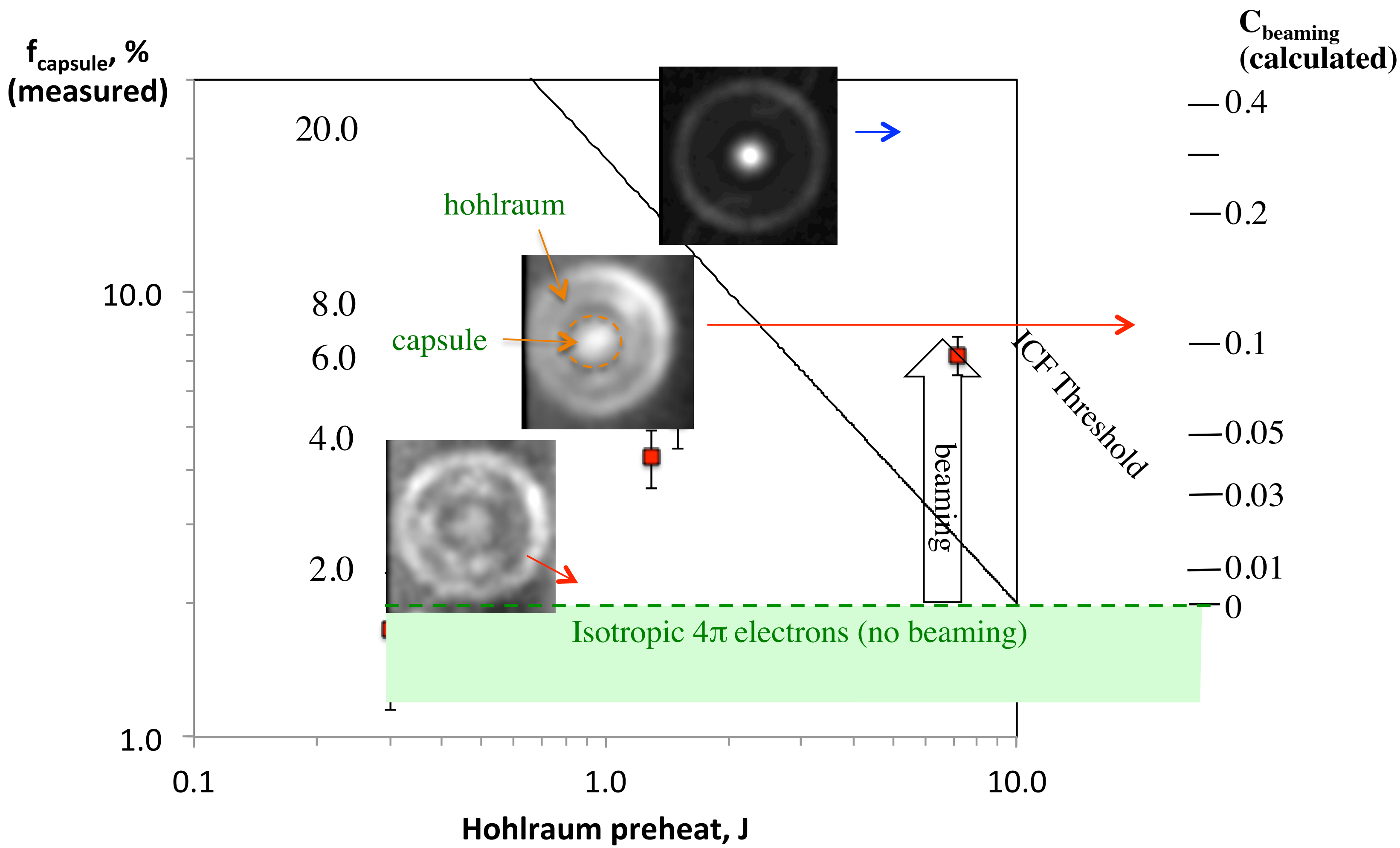
x-ray spectrum from Implosions



~CH shell should have ~50% of ICF capsule mass to maintain hydro and ablate by hot-e history

* Izumi, Hall

Dewald et al., strive to measure hot electrons fraction Deposited in the capsule and their spatial asymmetry



The Standard 4 Shock Temporal Pulse Shape of NIF with STUD Pulses Superposed: $f_{dc\%}$ = 20 in the Foot with T_{pulse} fixed and $f_{dc\%}$ = 50 in Main Drive with I_{max} Fixed.

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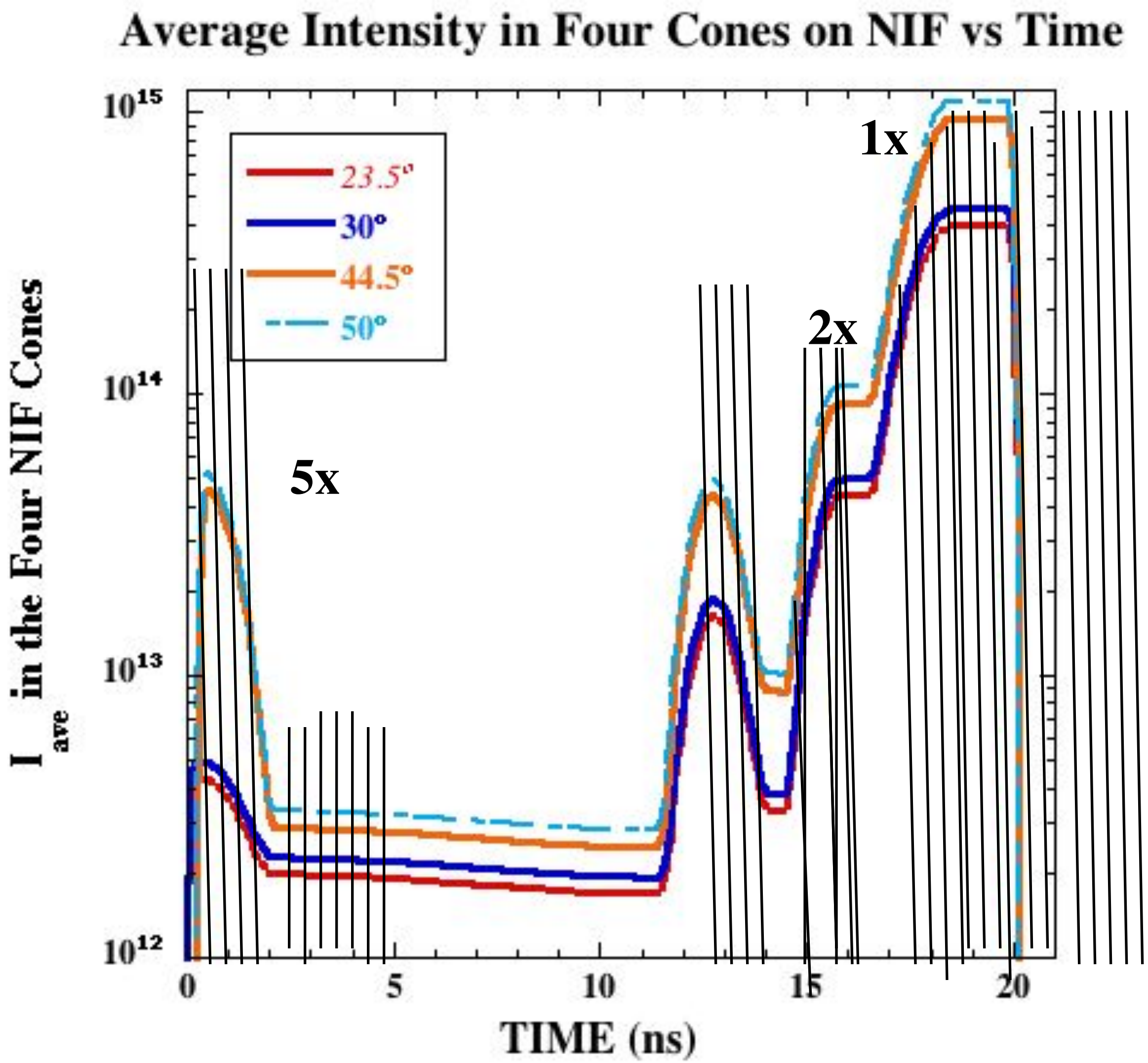
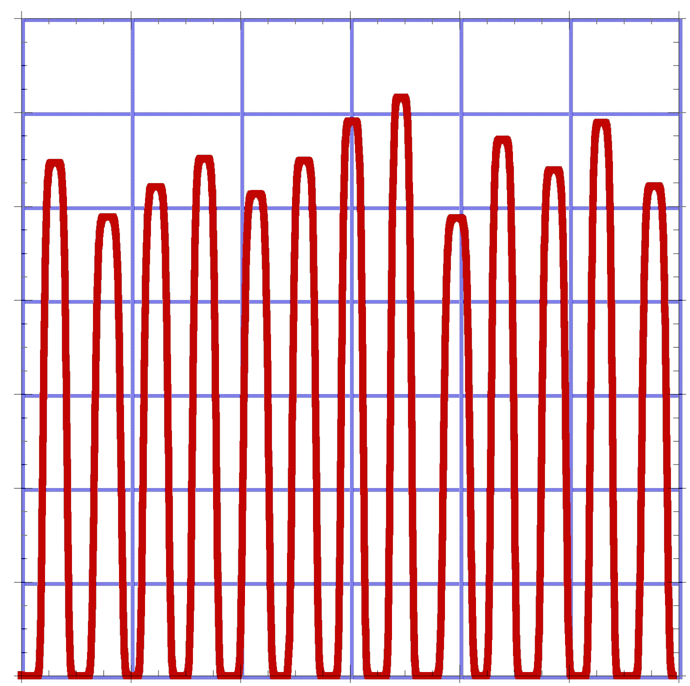


Large gaps in the foot (4 to 1) for interlacing cones and quads.
T_{Max} fixed
50% duty cycle during the main (twice as long) drive. I_{Max} Fixed.



A Good Design Space for T_{pulse} Fixed STUD Pulses Is 2010-5010 x1, 1:1:1/2 down to 1:1:1/4

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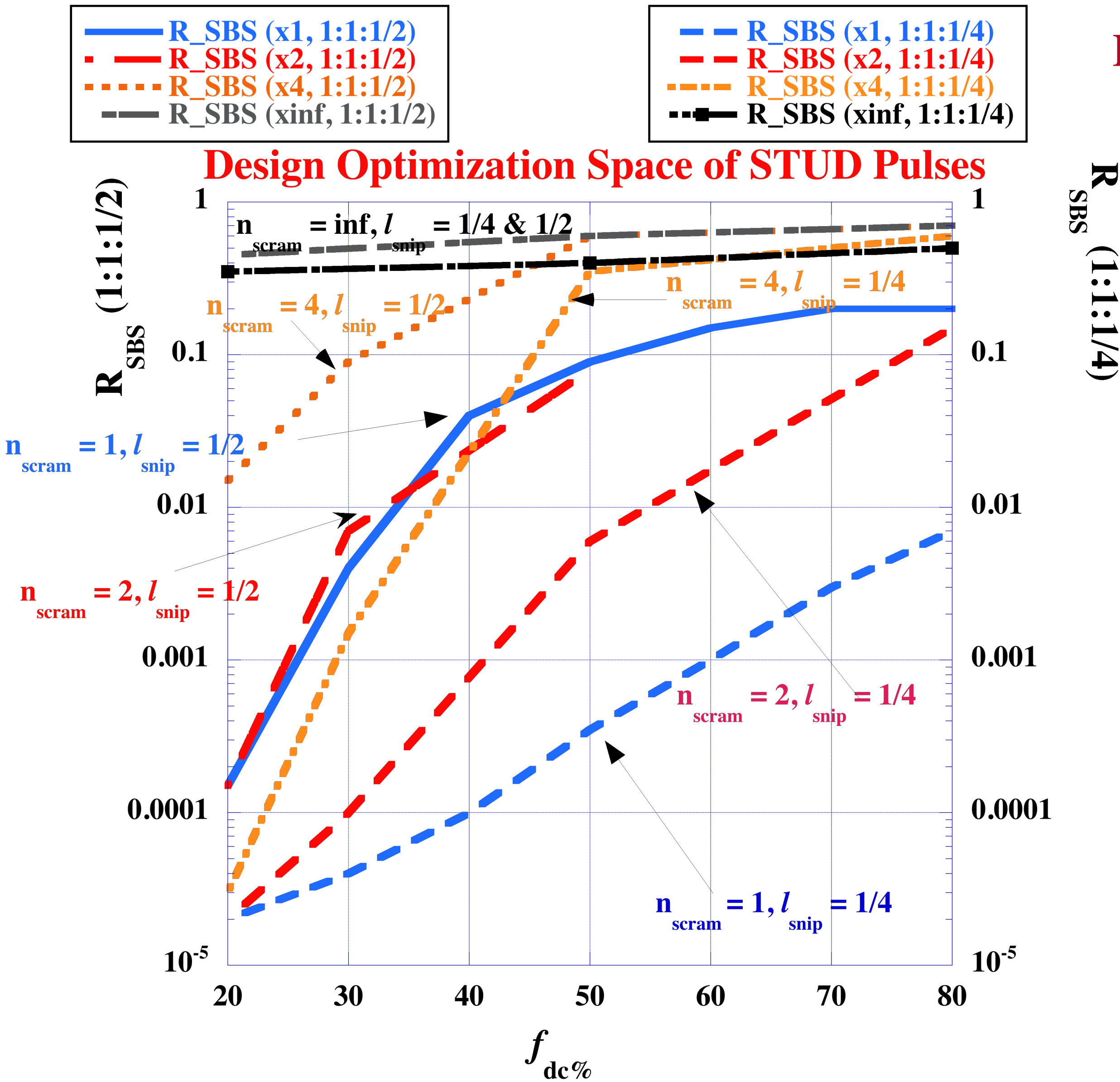
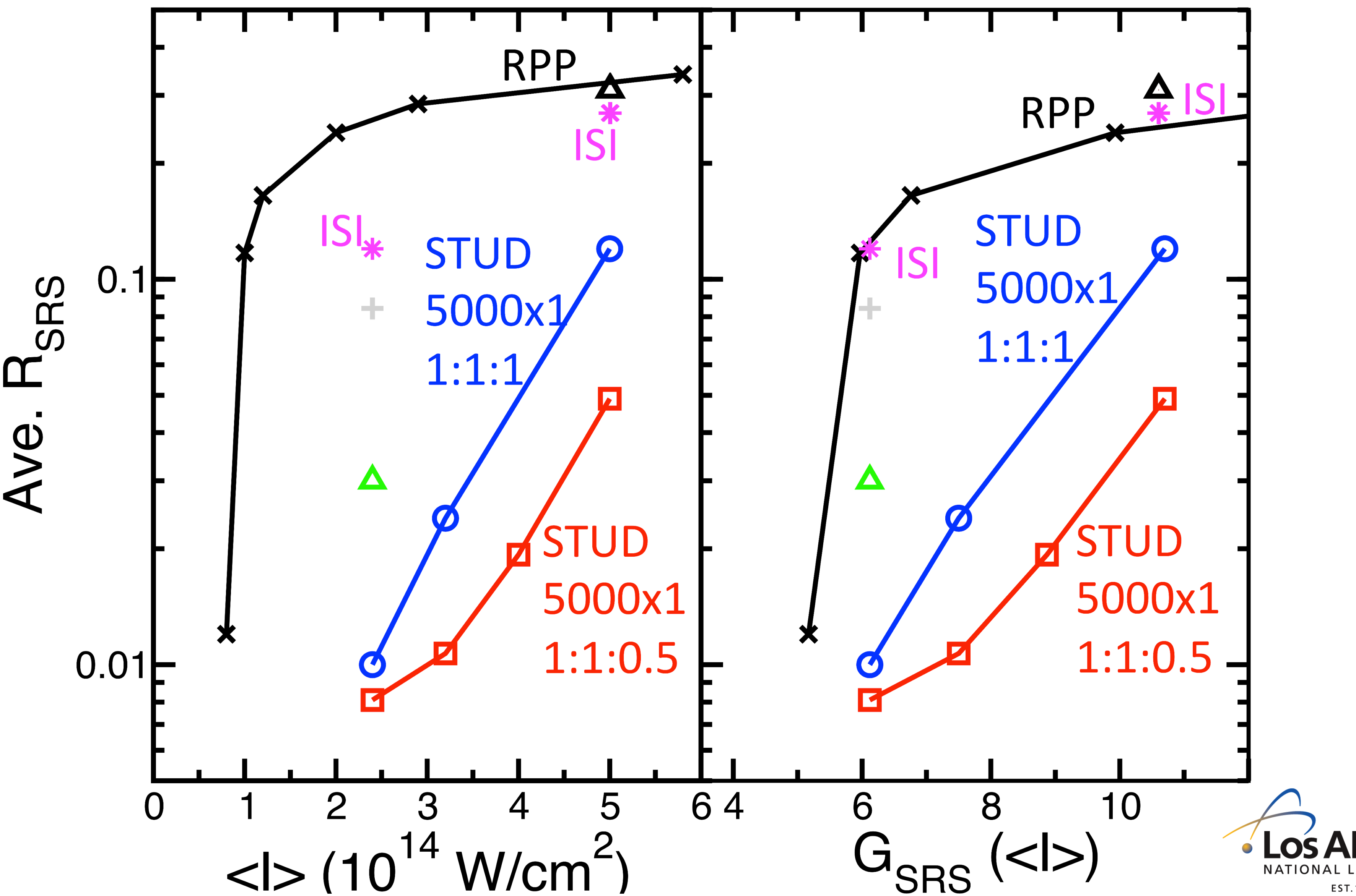
Harmony Simulations



VPIC Simulations Demonstrate Strong SRBS Reduction Using STUD Pulses in NL Kinetic Regime



5 Ingredients Are Needed to Execute the STUD Pulse Program on NIF:

- **Implement the SPA ACE Design of STUD Pulse Generation with 1-3 ps features lasting for 250 ps per box. Stack four boxes to get 1 ns. Repeat.**
- **Conduct experiments on Trident and Jupiter to test LPI control concepts via STUD pulses:**

  Use SPA ACE boxes. Develop and field fast diagnostics: OUFTS, etc. Measure df/dv (t).
- **Model CBET and SBS with deterministic to random STUD pulses in any Z plasma regime: from weak to strong damping limits and from weak to strong coupling regimes. Include any angle crossing beams: resolve laser wavelengths, 2nd order in space.**

[a] Model laser propagation through NIF architecture with STUD pulses. Have parallel modeling capability of STUD pulse propagation in laser media as well as in plasmas of interest. 3ω and 2ω

- **Design targets with lower average power, lower radiation temperature but with higher capsule to case ratio and thinner ablators: more suitable for LPI control. Can this win?**

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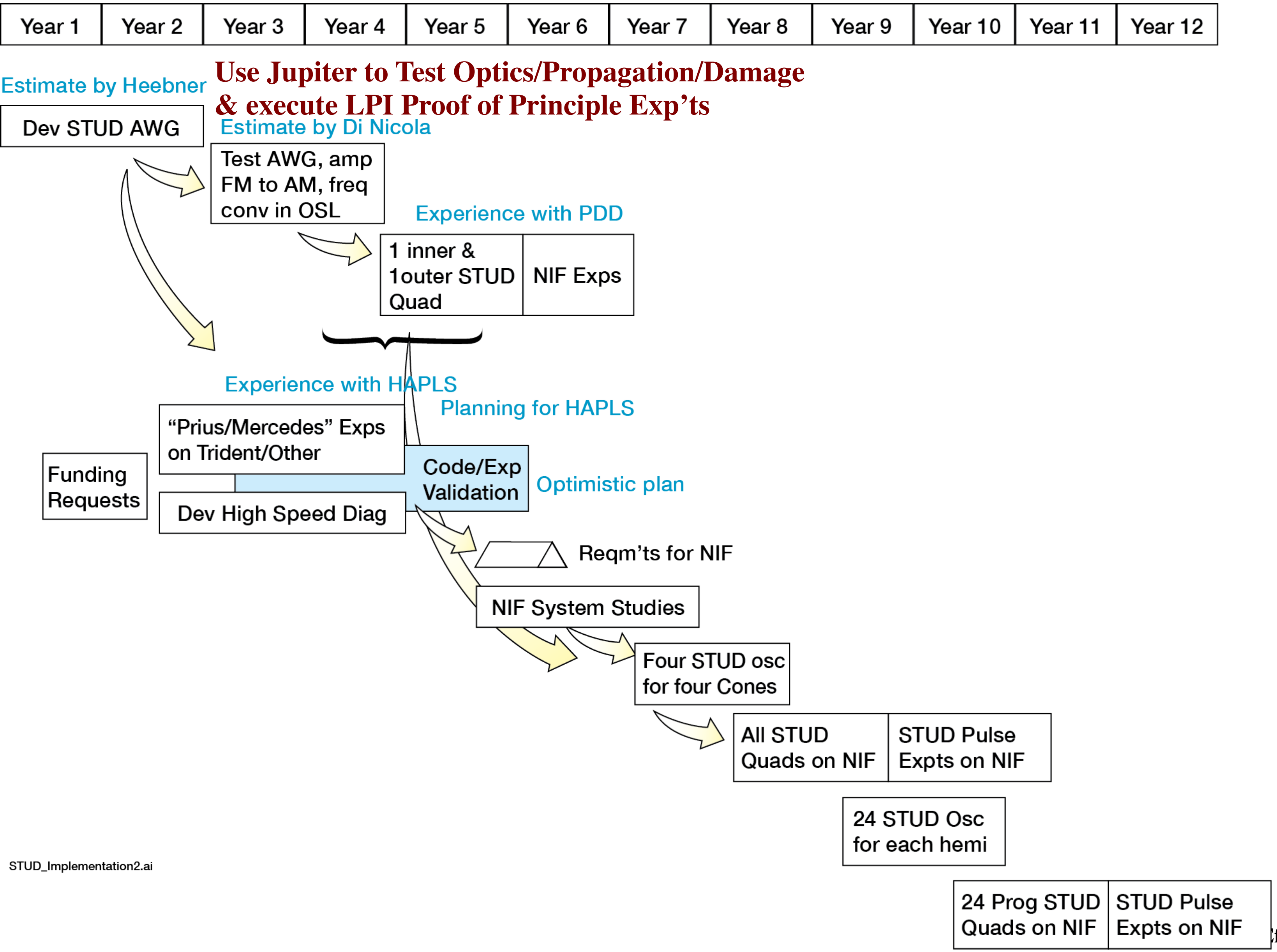
How Might A STUD Pulse Program on NIF Evolve over Time If Not Made into a Priority?



How Can We Measure the e$^-$ VDF of a Fast Nonlinearly and Kinetically Evolving Plasma?

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- Use Pump-probe near backscatter geometry with a burst of spikes as the pump.

- Measure the transmission or gain of the probe.

- Back out plasma conditions and isolate the e$^-$ or ion VDF information via the kinetic Landau damping rate.

- Compare neighboring regions at the same or nearby densities. Back out the extend of large beam nonlinear phenomena by a control burst of weakly nonlinear interactions under our control with small signal gain.

- Design sequences of spikes in successive STUD pulses so as to have unambiguous evidence of what is taking place in a quiet or highly agitated plasma.

- Designing the right STUD pulse sequences based on previous shots and optimizing and automating the procedure is the key.

Extract the ps Time Scale Evolution of the e⁻ VDF $v\{df(t)/dv\}$ Using STUD Pulses and SRS/SBS

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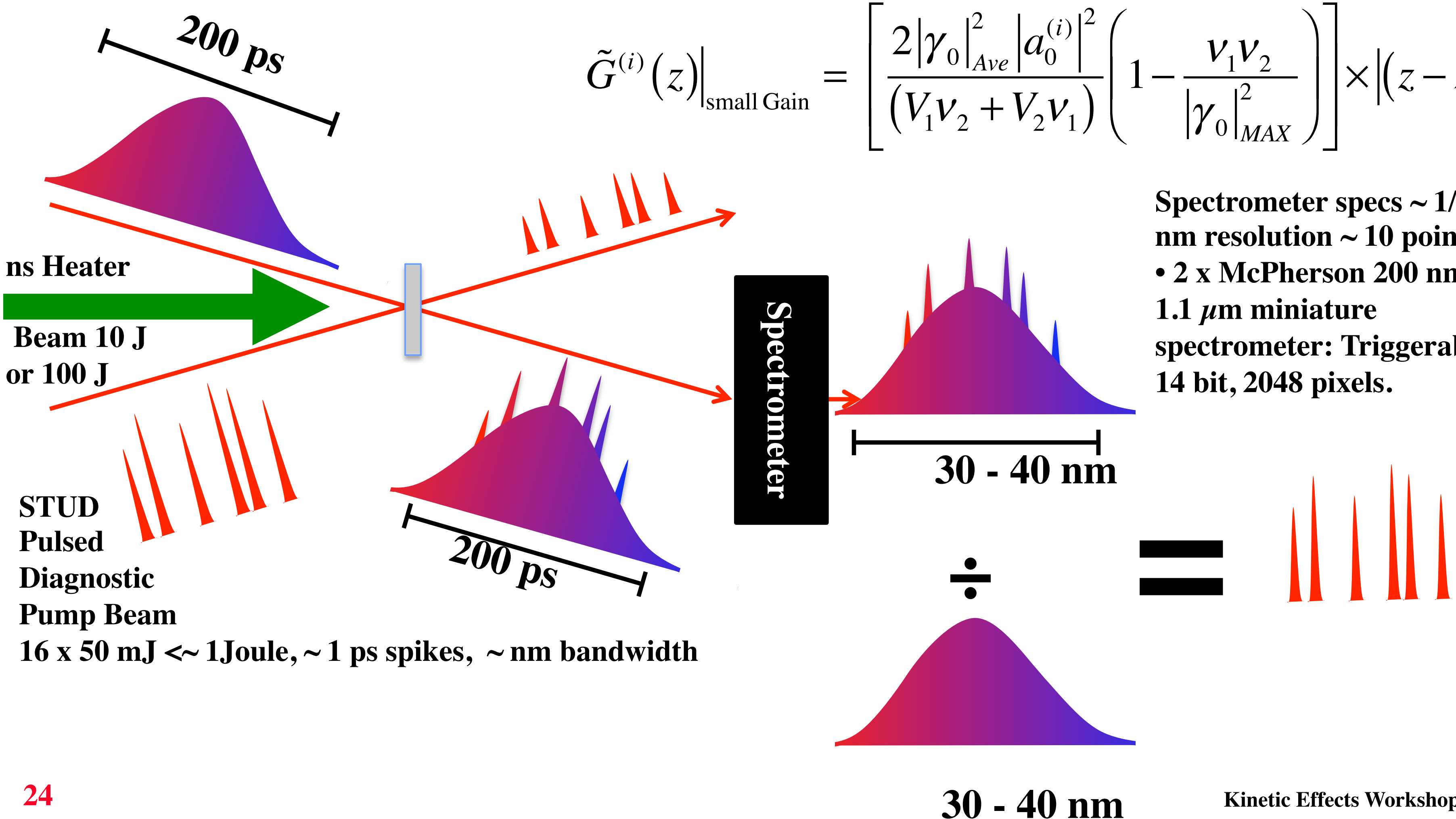
Probe Diag. Beam either a spectrally broadened and then stretched fiber laser, 1 μm wavelength, ~200 psec, ~ μJ, ~30 nm FWHM bandwidth. Amplitude Technologies, Imra.

Or a Ti:Sapphire pumped OPA tunable from 1 μm to 2 μm and doubled to cover 500 nm to 1 μm, ~100μJ, ~30 nm FWHM bandwidth. Coherent or Spectra Physics off the shelf.

The probe diag. beam is chirped so as to encode time to frequency at spectrometer: 5 ps / nm

$$\tilde{G}^{(i)}(z)\Big|_{\text{small Gain}} = \left[\frac{2\left|\gamma_0\right|^2_{Ave}\left|a_0^{(i)}\right|^2}{\left(V_1\nu_2+V_2\nu_1\right)}\left(1-\frac{\nu_1\nu_2}{\left|\gamma_0\right|^2_{MAX}}\right)\right]\times\left|\left(z-z_R\right)\right|$$



Spectrometer specs ~1/10 nm resolution ~10 points

- **2 x McPherson 200 nm – 1.1 μm miniature spectrometer: Triggerable, 14 bit, 2048 pixels.**

STUD Pulsed Diagnostic Pump Beam
16 x 50 mJ <~ 1Joule, ~1 ps spikes, ~nm bandwidth

How Does SRS Amplification Evolve in Time with and w/o STUD Pulses?

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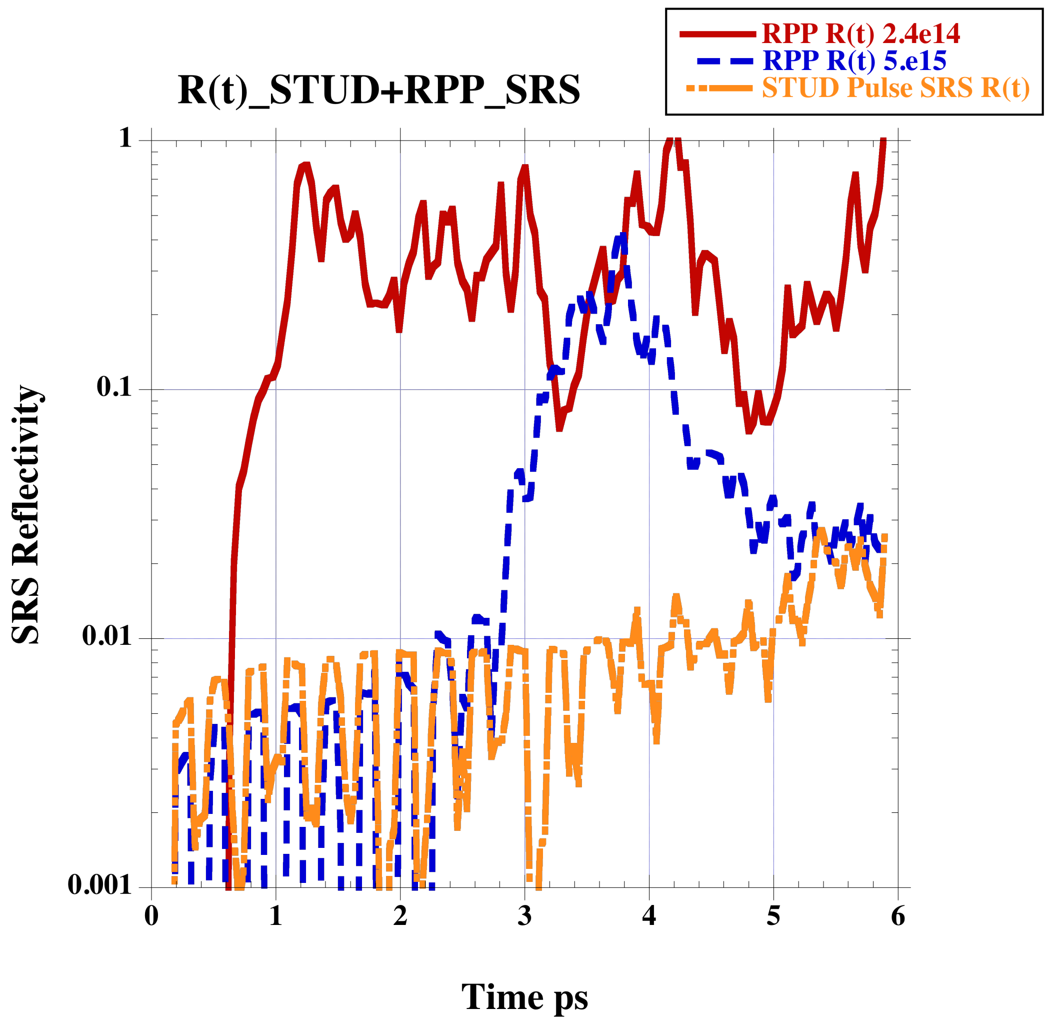

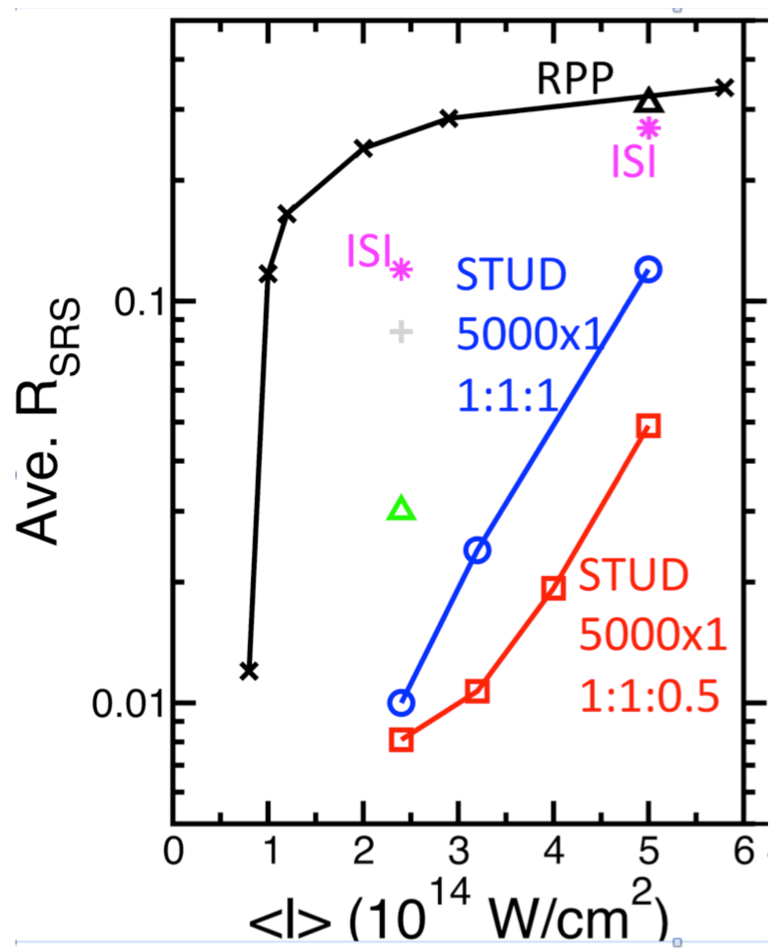

How Are e⁻ VDF's Modified In the Presence of Highly Nonlinear Kinetic SRS?

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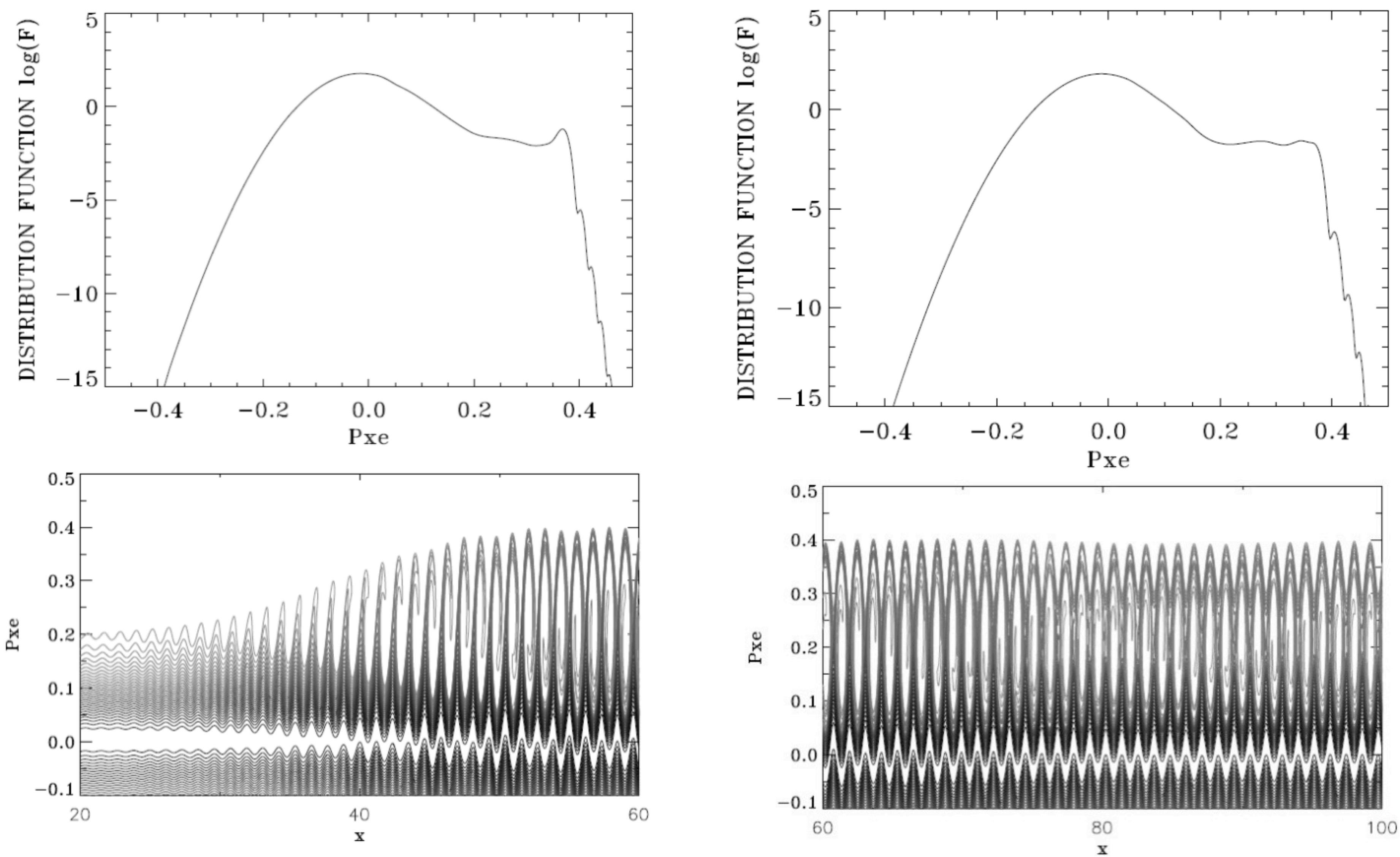
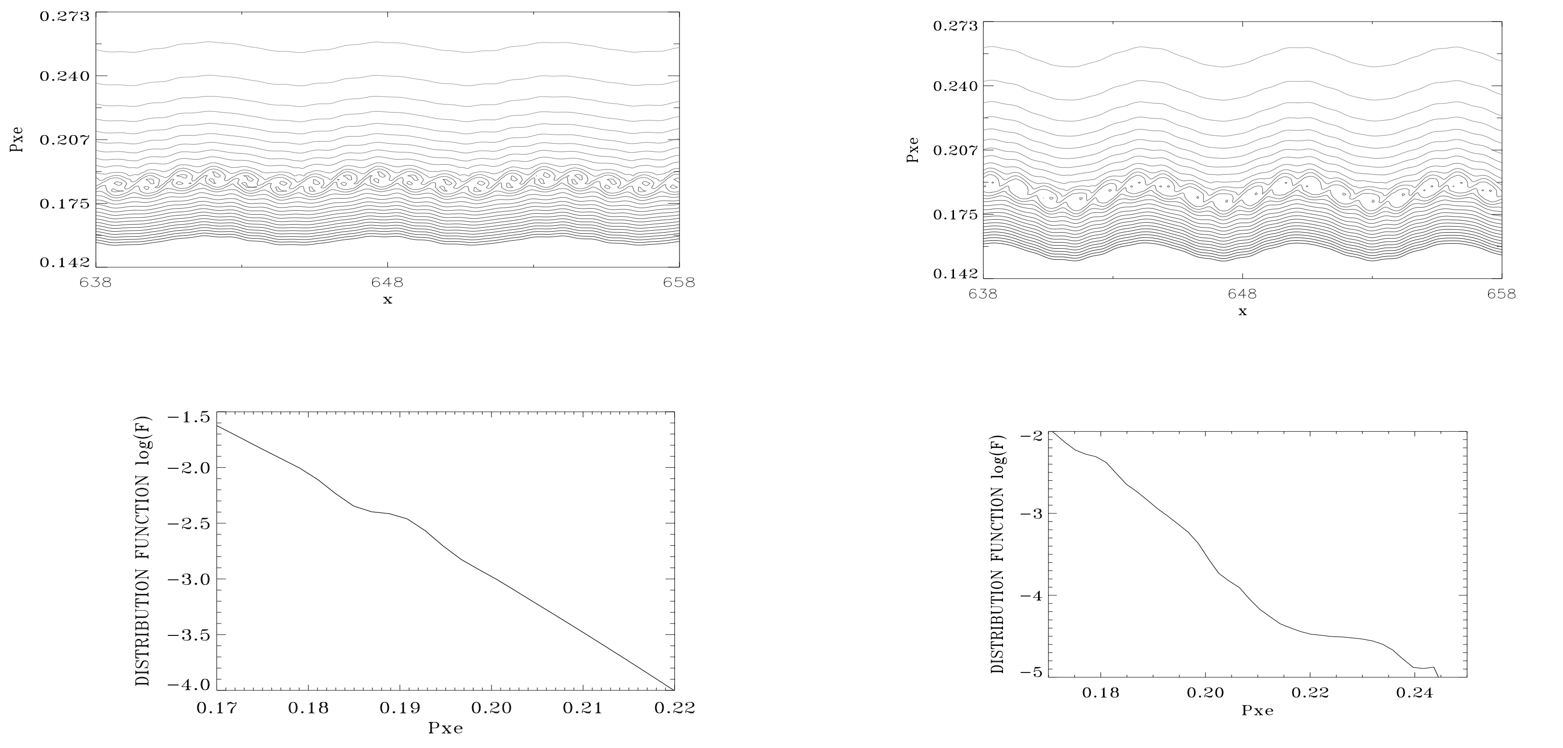


How About More Esoteric States? SRS + SKEENS



http://www.intechopen.com/books/references/computational-and-numerical-simulations/stimulated-raman-scattering-with-a-relativistic-vlasov-maxwell-code-cascades-of-nonstationary-nonlinear-interactions

Take Away Points

- New experiments are proposed to follow the hot e^-s wherever they may roam.
- New diagnostics are proposed to extract the e^- and ion distribution functions from localized regions of space and on very fast time scales (using STUD pulses)
- New physics models can tie hot e^- intermittent bursts to shocked interfacial physics with new features that affect ablator and fuel symmetry directly, which degrade implosion performance significantly in a myriad of ways.
- It is worth pursuing the consequences of a ns worth's of x 10 kJ of hot electrons above 170 keV bathing the hohlraum, in high foot implosions.
- Once a tenth of these hot e-s are absorbed into the dense fuel in a highly asymmetric M8/M16 way, they will preferentially heat ions nonuniformly and thus burn nonuniformly.
- It is important to set limits on radiation drive asymmetry and hot e^- pre-heat and late time bombardment asymmetry that unmistakably disallow symmetric fusion burn propagation.

Theory of Two Plasmon Decay in Inhomogeneous Multidimensional Nonuniformly Illuminated Plasmas

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$$\left|\tilde{v}_0\right|^2 = \frac{\left(I_{\mathrm{KE}} + I_{\mathrm{PE}}\right)}{I_{\mathrm{NORM}}}$$

Minimum Pump Strength-Variational Principle (MPSP)

B. B. Afeyan & E. A. Williams, Phys. Plasmas 4, 3827 (1997)

$$L_{\mathrm{KE}} = \frac{1}{4}\left(\bar{d}_{l_2} - d_{l_1}\right)^2 \bar{\nabla}^2 \nabla^2$$

$$L_{\mathrm{PE}} = \bar{\nabla}^2 \nabla^2 V^2$$

$$L_{\mathrm{NORM}} = -\left|u_0(\mathbf{x})\right|^2 \left(\hat{\mathbf{u}}_0 \bullet \nabla\right)^2 \frac{\left(\bar{\nabla}^2 - \nabla^2\right)^2}{\varepsilon}$$

$$I_j \equiv \left(\tilde{\Psi}, L_j \Psi\right)$$

Hidden Under the Rug of the MPS-VP for $2\omega_{pe}$ Are these Definitions

$$\bar{d}_{l_2} = (\omega_0 - \omega_1)^2 \left(1 - \frac{i\nu_2}{\omega_0 - \omega_1}\right) - \omega_p^2(\mathbf{x}_0) + \mathrm{v}_\mathrm{E}^2\, \bar{\nabla}^2$$

$$d_{l_1} = \omega_1^2 \left(1 + \frac{i\nu_1}{\omega_1}\right) - \omega_p^2(\mathbf{x}_0) + \mathrm{v}_\mathrm{E}^2\, \nabla^2$$

$$\bar{\nabla} \equiv \nabla - i\,\mathbf{k}_0$$

$$V \equiv \omega_p^2(\mathbf{x}) - \omega_p^2(\mathbf{x}_0) = \varepsilon_\mathrm{L} z$$

$$\tilde{\mathrm{v}}_0 \equiv \left(\frac{\mathrm{v}_0}{\mathrm{c}}\right)\omega_p(\mathbf{x}_0)\frac{\sqrt{\varepsilon}}{2}$$

$$\mathrm{v}_\mathrm{E}^2 \equiv \frac{3\,\mathrm{v}_\mathrm{th}^2}{\mathrm{c}^2}$$

$$\tilde{\beta} \equiv \frac{\sqrt{\varepsilon}\,\mathrm{v}_\mathrm{E}^2}{|\tilde{\mathrm{v}}_0|} = 2.75\frac{T_{\mathrm{e,keV}}}{\left(\mathrm{I}^{1/2}_{14\mathrm{W/cm}^2}\lambda_{0,\mu m}\right)}$$

$$\varepsilon \equiv 1 - \omega_p^2(\mathbf{x}_0)$$

$$\varepsilon_\mathrm{L} = \frac{\omega_p^2(\mathbf{x}_0)}{\left(\frac{\omega_0 \mathrm{L}}{\mathrm{c}}\right)}$$

$$\omega_p^2(\mathbf{x}_0) \approx \frac{1}{4} - \mathrm{v}_\mathrm{E}^2\left(k_1^2 + k_2^2\right) + \mathrm{v}_\mathrm{E}^4\left(k_1^2 - k_2^2\right)^2 \Big/ 4$$

$$\frac{1}{4}\left(\bar{d}_{l_2} - d_{l_1}\right)^2 = \left[\Omega - \frac{1}{2}\mathrm{v}_\mathrm{E}^2\left(\bar{\nabla}^2 - \nabla^2\right)\right]^2$$

$$\omega_1 = \omega_p(\mathbf{x}_0) + \bar{\varpi}$$

$$\omega_2 = (\omega_0 - \omega_1) - \bar{\varpi}$$

$$\Omega = \bar{\varpi} - \mathrm{v}_\mathrm{E}^2\frac{\left(k_1^2 + k_2^2\right)}{2} + i\frac{(\nu_1 + \nu_2)}{4}$$

$$\Re(\omega_1) = \frac{1}{2} + \Re(\Omega)$$

$$\Im(\omega_1) = \Im(\Omega) - \frac{(\nu_1 + \nu_2)}{4}$$

The Growth Rate of the Most Unstable Mode of $2\omega_{pe}$ in an Inhomogeneous Plasma Is:

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$$\mathrm{Im}\left[\omega_{EPW}^{2\omega_{pe}}/\omega_0\right] = \tilde{\mathrm{v}}_0 \left\lfloor 1 + \frac{(v_1 + v_2)/\omega_p}{8\tilde{\mathrm{v}}_0} - \frac{1}{2}\tilde{\beta}^2\eta^2 - \frac{\varepsilon_L}{2\tilde{\mathrm{v}}_0|\eta|} \right\rfloor$$

$$\tilde{\mathrm{v}}_0 = \frac{1}{2}\sqrt{\varepsilon}\left(\frac{\omega_P}{\omega_0}\right)\frac{\mathrm{v}_0}{c} = 1.85\times 10^{-3}\sqrt{I_{14,W/cm^2}\lambda_{0,\mu m}^2}$$

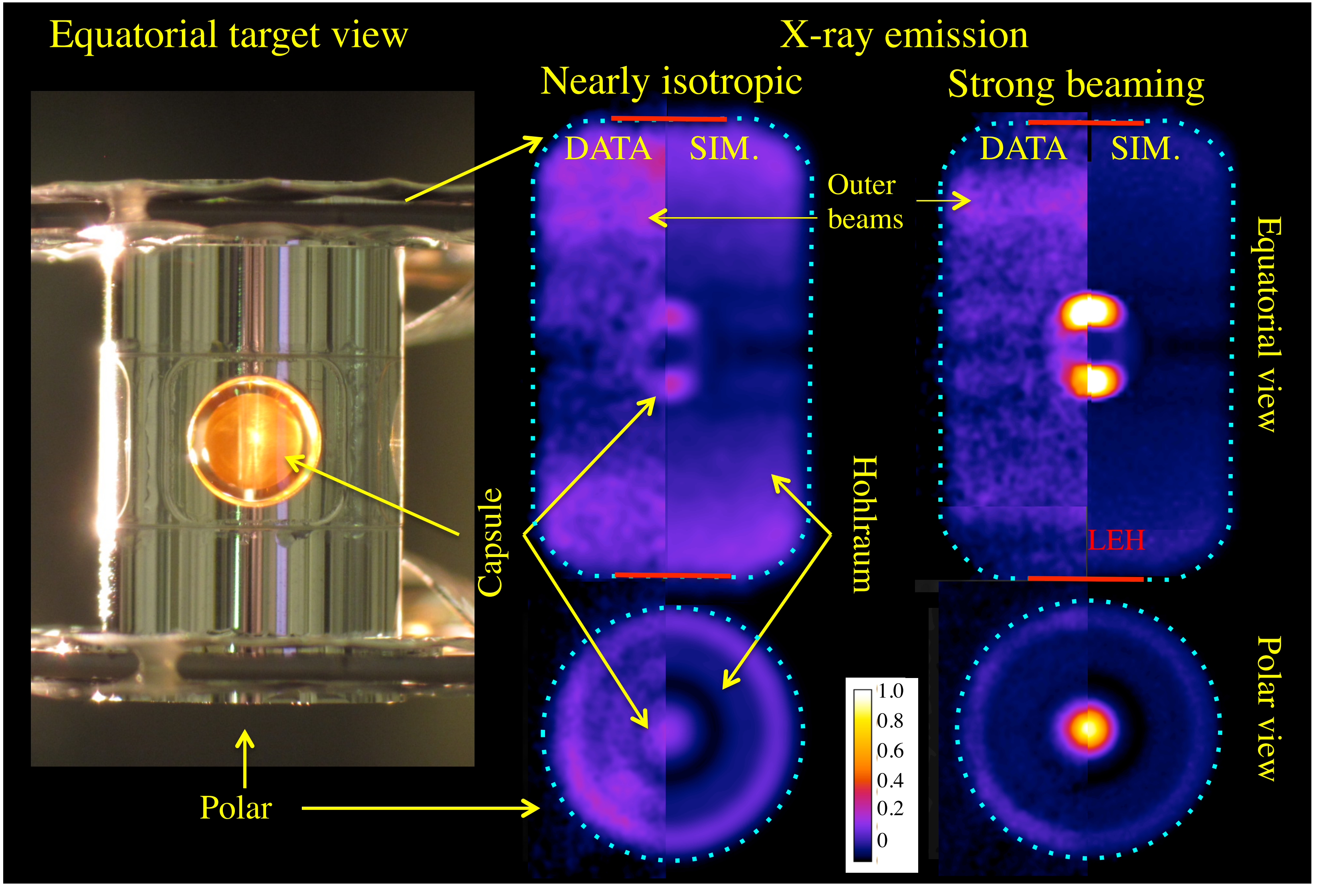
$$\varepsilon_L = \frac{\omega_p^2/\omega_0^2}{(\omega_0 L/c)}$$

$$\eta = \frac{ck_\perp}{\omega_0}$$

$$\tilde{\beta} = 12\frac{(\mathrm{v}_{th}^2/c^2)}{(\mathrm{v}_0/c)} = 2.75\frac{T_{e,keV}}{\sqrt{I_{14,W/cm^2}\lambda_{0,\mu m}^2}}$$

$$I_{14,W/cm^2} \geq 0\,54\frac{T_{e,keV}}{L_{n,100\mu m}\lambda_{0,\mu m}}[1-\bar{v}]^{-3/2}$$

Dewald Experimental Platform Measuring Hot e⁻s by their Hard X ray Bremsstrahlung Signatures



* E. Dewald et al, Phys. Rev. Lett. 2016